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Natural Rubber - Producing Plants for the United States

Cooperative
State
Research
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Natural Rubber-Producing Plants for the United States

prepared by

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Foreword

The mission of the Office of Agricultural Industrial Materials is to accelerate commercialization of non-food, non-feed industrial products from agricultural raw materials, both plant and animal. It is one of many programs which focus on providing U.S. farmers with alternative opportunities to traditional enterprises and practices in a changing domestic and global economy.

One of the most basic needs in a commercialization project is developing the agricultural capability for reliable supply of high quality materials to processing and manufacturing operations. These materials must satisfy certain physical and performance specifications and be profitable for farming and industry. This research report was undertaken to inventory rubber producing plants and to assess their relative importance as potential commercial crops in establishing a domestic natural rubber industry. To that end, we find that guayule (*Parthenium argentatum*) is the latex producing plant of greatest near term promise for commercialization and that other plants show varying degrees of potential.

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Project Note and Acknowledgements

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Natural Rubber-Producing Plants for the United States

Introduction

Rubber, *cis*-1,4-polyisoprene, is a natural product that generally, but not always, occurs within latex, a milky fluid contained in leaves, stems or roots. Latex, known from some 12,500 species in 900 genera and twenty families, consists of small particles in a liquid suspension (51). These particles are often hydrocarbons of the terpene type: essential oils, balsams, resins and rubber (51). The amount of rubber in latex varies considerably according to species, plant tissue, stage of growth, season of year and other factors. In many species, the rubber fraction is too contaminated with resins to be commercially useful (51).

Moyle (54) listed 554 species (mostly tropical) known to produce rubber and noted that few had been exploited commercially. A more recent tally of rubber-producing plants is that of Polhamus (61), who reported that rubber was known from 1,117 species.

The principal rubber plant of commerce is *Hevea brasiliensis* (Willd. ex A. Juss.) Muell.-Arg. At various times and places, other species have also been important rubber producers, among them *Castilla ulei* Warb., *Castilla elastica* Cerv., *Manihot glaziovii* Muell.-Arg., *Manihot dichotoma* Ule, *Ficus elastica* Roxb., *Funtumia elastica* Stapf and *Parthenium argentatum* Gray (54). All, with the exception of *Parthenium argentatum*, are native to the tropics or subtropics.

Over the past six decades, the United States government has funded several programs aimed at developing a domestic rubber supply. The first occurred in response to World War I (36, 37). Sporadic interest continued in the period between the wars (for example, 6, 7, 27, 38, 59, 63). The inventor Thomas A. Edison independently organized the collection and analysis of several thousand plant species during this time (61, 62). During World War II, when supplies of natural rubber were cut off by the Japanese occupation of the Dutch East Indies and other rubber-producing areas in the Southwest Pacific, the search for and development of domestic rubber plants accelerated (see, for example, 15, 29, 42, 53, 81, 84). However, natural rubber from wild sources produced only 100,000 tons of the rubber used in the United States between 1942 and 1944 (84), and in the end, it was not the hastily developed supplies of natural rubber that filled the war-time gap but the rapid development of synthetic rubber instead (25, 50). After the war, the use of synthetic rubbers grew rapidly; it quickly became apparent, however, that synthetics, made from petrochemical feedstocks, could not substitute for natural rubber in all cases, and natural rubber remained the raw material of choice for heavy-duty tires and other industrial uses requiring elasticity, flexibility and resilience (5, 61). More recently, because of the increasing price

and decreasing availability of petroleum, the 1970s and 1980s have seen renewed interest in the production of industrial and chemical feedstocks, including rubber, from plants (11). The USDA Northern Regional Research Center in Peoria, Illinois, for example, has analyzed some 1,000 species for rubber and other botanochemicals (22).

In 1978 the U.S. Congress passed public law 95-592, the Native Latex Commercialization and Economic Development Act, designating *Parthenium argentatum* as the official crop for domestic production of natural rubber, leading Buchanan et al. (14) to conclude that, while further development of other high-molecular-weight rubber crops is unlikely, there is still a viable market for domestic, low-molecular-weight, natural rubbers. Paterson-Jones (58), on the other hand, stated that there was little point in South African scientists hunting for native rubber crops since *Parthenium argentatum* will grow in South Africa and, furthermore, has benefited from seventy years of crop development.

Economics of Domestic Rubber Production

In the late 1970s, consumption of *Hevea* rubber in the United States was 800,000 tons per year at a price of $0.90 per kilogram [$0.40 per pound] (13). Synthetics, which accounted for 2,600,000 tons of domestic rubber consumption, cost $0.75 per kilogram [$0.33 per pound]. The price of synthetic rubber is directly related to that of petrochemical feedstocks derived from fossil fuels, thus synthetic rubber prices tend to move up and down with the price of oil.

Researchers seeking new supplies of natural rubber have long recognized that any likely source must be able to compete with *Hevea* rubber (and now with synthetics) in quality and price (36). Martin (45) pointed out that most of the tropical trees and lianas known to contain rubber were "hopelessly outclassed" by *Hevea* in quality, yield and ease of treatment; however, he added, small plants that could be treated as agricultural crops might be effective competitors since their cultivation and processing could be mechanized. Unfortunately, the majority of rubber plants that could be grown in the United States combine low rubber content with moderate plant biomass, and, until their yields are improved, the cost per acre of producing rubber makes it unlikely that home-grown rubber will be able to compete with *Hevea* under normal circumstances. Domestic rubber must compete not only with *Hevea* but with other land uses, as well (45), whether these involve agriculture or industrial development.

Buchanan et al. (11, 12) set a goal of developing U.S. rubber crops that would be as productive as *Hevea*, which, in southeast Asia, annually produces 2.24 tonnes of rubber per hectare. To achieve this level of production, it would be necessary to develop a crop that contained ten percent oil and hydrocarbon and yielded 22,416 kilograms of dry matter per hectare per year (11, 12). Buchanan and Otey (13) calculated that *Asclepias syriaca* L. would be economically feasible as a rubber crop if it yielded 13.5 kilograms of dry matter per hectare per year and contained ten percent polymeric hydrocarbon, six percent oil and seven percent polyphenol. This would necessitate a fifty percent improvement in its dry-matter yield and a two- to three-fold increase in its hydrocarbon content (13). In general, rubber crops are economically feasible only if they can also be processed for such coproducts as specialty chemicals, resin, protein, fiber and oil (11, 12).

It has been suggested that rubber and other hydrocarbon crops should be grown on land not suited for conventional crops, and the arid regions of the southwestern United States are often singled out as a likely location. However, the cost of water (particularly the price of energy for pumping groundwater) may reduce the competitiveness of botanochemical crops in the Southwest (48).

Evaluation of Potential Rubber Crops

Since the early 1900s, American scientists have evaluated several thousand species as potential rubber plants. Some of the earlier work is of limited value since the analytical methods used often failed to distinguish among the various kinds of hydrocarbons present in the sample (11). Earlier investigators (for example, 36, 37, 38, 60) generally removed hydrocarbons from dried, ground plant material by first extracting the sample with acetone, then extracting the residue with benzene. Occasionally the benzene fraction was characterized as rubber or gutta-percha by further analysis. In recent years, the technique most often used has been extraction of dried, ground plant material with acetone followed by cyclohexane or hexane extraction (see, for example, 12). Newer studies are most valuable when they present quantitative measures of rubber quality.

The notion of how much rubber a plant must contain if it is to be a useful source of rubber has changed over the years. Martin (45) stated that rubber should comprise at least ten percent of a plant's dry weight. Polhamus (60) examined numerous species, some of which contained as much as seven percent rubber, yet concluded that his survey had identified "no new valuable rubber crop." As early as 1921, however, certain investigators stated that plants containing one to eight percent rubber showed potential (38), and, more recently, scientists have nominated candidates containing as little as 0.7 percent hydrocarbon (22, for example). Buchanan et al. (12) considered species having a hydrocarbon content of over two percent to be promising, but recognized that this proportion must be increased several times for crop development to be practicable.

With the availability of sophisticated analytical techniques – infrared spectroscopy in particular – researchers have been able to resolve the hydrocarbon fraction into natural rubber, oil, resins and other components. In the past, resins have been considered a liability in rubber crops. When present in too high a proportion, they can make plants more difficult to harvest, and they tend to produce rubber that is soft and sticky or hard and brittle (51, 61). Now, however, it is recognized that when resins can be separated from the rubber, they may constitute a potential source of revenue that adds to the overall value of the crop (57).

Determining rubber content of a species is only a first step in determining its potential value as a rubber crop. As Paterson-Jones noted, "The analysis of the rubber contents of plants on a dry-weight basis does not provide a means of identifying possible producers of rubber latex which could be tapped [or cultivated]. For this purpose a determination of the quantity and quality of the rubber produced from the latex would be necessary" (58). Most reports contain at least a word or two about the quality of rubber produced by a given species. Generally, this evaluation has been highly subjective, based on the literal feel of the extracted product. Recent workers (78, for example) generally base their definition of rubber quality on more objective criteria, such as molecular weight and molecular weight distribution. Gel permeation chromatography now makes it

possible to determine molecular weight of rubber from various plant sources. Molecular weight and molecular weight distribution indicate the processability of a natural rubber; in general, the higher the molecular weight, the greater the processability (78). The molecular weights of *Hevea* and *Parthenium argentatum* are extremely high – 1,310,000 and 1,280,000, respectively (22) – and so far, no other plants native to the United States approach these values. Even the most likely candidates have molecular weights of only 200,000 (marginally useful) to 500,000 (78). Still, should the need to use domestic rubber plants prove pressing, low-molecular-weight rubbers could be used as plasticizing additives, in liquid rubber processing methods, for making cements and as hydrocarbon feedstocks (14).

In addition to data on rubber content and quality, an estimate of plant biomass is also necessary. This makes it possible to determine rubber yield on a per-hectare basis. For all but a few native species, this kind of information simply does not exist, and gathering it should be among the first objectives of any research and development program.

Selection and Breeding of Rubber Crops

Selection, in the plant breeder's sense of the term, means identifying the best plants, saving their seeds and growing them out, a process that is repeated as often as necessary to enhance the desired quality. Breeding means cross-pollination of particular strains or populations of plants. (Cross-pollination is the natural or artificial transfer of pollen from the anthers of one plant to the receptive stigmas of another.) Selection and breeding are often combined: selected strains with desirable characteristics are crossed, then their progeny are selected and crossed, a process often repeated many times over decades. With rubber plants, such a program could involve crossing one strain known for high biomass with another known for high rubber content.

Hevea is a prime example of selection and breeding in a rubber plant. Since its introduction into the Far East as a plantation crop, its yield and disease resistance have been substantially increased by crossing high-yielding Eastern strains with disease-resistant American strains (61). In 1935 Russian agronomists began an intensive selection and breeding program on *Taraxacum kok-saghyz* Rodin, starting with plants whose roots varied in weight from two to 150 grams and in rubber content from a trace to thirty percent. By 1940, they had obtained two strains with root weights of twenty-four and twenty-five grams and rubber percentages of 14.5 and 15.5 (84). Closer to home, breeders of *Parthenium* have worked with variable success on increasing its size, disease resistance, cold tolerance, rubber content and germinability (Polhamus 1962).

With the exception of *Parthenium argentatum*, little selection and breeding have been done on rubber plants that could be grown in the United States, and published statements regarding the breeding potential of native rubber plants should be regarded critically. Stipanovic et al. (77), noting that samples of *Helianthus annuus* L. had shown rubber contents of 0.26, 0.49, 0.55, 0.74 and 1.45 percent, concluded that there was a high potential for increasing the rubber content of cultivated sunflower. In this particular case (and in most others, as well) the investigators did not conduct the studies that would demonstrate whether or not the observed variation in rubber content is indeed under genetic control. As McLaughlin (49) pointed out, some researchers erroneously assume that phenotypic variation (differences in leaf size, stem height, rubber content, etc.) indicates breeding potential. In actuality, controlled experiments are necessary to determine what proportion of the phenotypic variation is genetically controlled and what proportion can be assigned to environmental factors and random variation (49). Claims such as those made for improvement in *Asclepias syriaca* (18, 19) are suspect in the absence of supporting genetic analyses (49).

Identifying Potential Rubber Plants

Appendix A is a catalogue of forty-six potential rubber plants selected from the literature according to the following criteria:

- amenable to mechanized agriculture
- cultivable within the continental United States and northern Mexico
- rubber content on a dry-weight basis of two percent or more (with some exceptions).

The catalogue is arranged alphabetically by family. Growth form, distribution, habitat and rubber content are noted for each species. Wherever possible, information on cultivation, molecular weight, dry-matter yield, breeding potential and potential coproducts has been provided.

Data for a number of rubber-containing species that did not meet the criteria listed above can be found in Carr (21), Carr et al. (23, 24), Cull (28), Gnecco et al. (34), Hall (35), Marimuthu et al. (44), Roth et al. (68, 69).

Appendix B summarizes the information presented in **Appendix A**. The list is arranged alphabetically by species. Included are scientific name; plant family; region of distribution; rubber percentage; molecular weight of rubber, when known; and coproducts, if any.

Appendix C is a catalogue of the major tropical species (other than *Hevea brasiliensis*) known to produce rubber. Additional tropical plants are mentioned by Moyle (54) and Polhamus (61). These species possess two major disadvantages as far as domestic rubber production is concerned: first, most of the continental United States is not suitable for their cultivation, and, second, virtually all must be tapped, an expensive and tedious procedure that, in the United States, would raise the cost of their rubber far above that of imported *Hevea*.

Between 1927 and 1931, Thomas A. Edison organized an investigation of rubber plants. Under his supervision, more than 2,000 species were examined for their rubber content. This work, detailed by Polhamus (62), is of modest value, in part because of the imprecise laboratory techniques used to evaluate the hydrocarbon fraction and in part because of the low number of samples analyzed (often only one or two for a given species). Edison's results, however, might be useful in guiding future investigators: for example, he found rubber contents of 2.43 to 3.63 percent in several species of *Aster*, a genus that has been largely overlooked by more recent investigators. **Appendix D** lists all the species Edison found to contain a mean of two percent or more of rubber (data extracted from Polhamus (62).

Conclusions

As **Appendix A** shows, *Parthenium argentatum* is at present the best candidate as a potential source of domestic rubber for the United States. As the focus of seventy years of agronomic and breeding research, it has been investigated to a far greater extent than any other rubber-producing plant native to North America. If, as seems likely, higher-yielding cultivars can be bred, commercial rubber production from guayule should be economically feasible. Since the species is well-adapted to cultivation in arid regions, it provides a low-water-use alternative to more water-intensive crops such as cotton and sorghum.

Should full-scale development of other rubber crops prove desirable, research efforts could be directed in two different channels. One is to continue screening wild plants for rubber. Species found to contain appreciable amounts of rubber (two percent or more) should routinely be subjected to further scrutiny to determine the molecular weight and molecular weight distribution of the rubber. If the molecular weight is low (between 200,00 and 500,000), the value of potential coproducts may determine whether further research and development are worthwhile. Other factors to consider include plant biomass, seasonality of rubber production and amenability to mechanized agriculture.

Research efforts could also focus on the species already identified as rubber-producing plants. Molecular weights and molecular weight distribution are known for only a few, yet these values are critical in evaluating the potential usefulness of any rubber plant. Plant biomass must also be estimated, since yield of rubber per unit area is a function of rubber content and biomass produced. Agronomic evaluations should include seasonality of rubber production and amenability to mechanized agriculture. Selection and breeding can dramatically increase rubber content, but only if the species possesses useful genetic variation for rubber yield. This characteristic, known for very few species, can be determined experimentally. Economic analysis of candidates should include the value of potential coproducts; in some cases, these may have a higher market value than the rubber itself.

Appendix A
Catalogue of Selected Rubber-Producing Plants for the United States

Apocynaceae

Amsonia palmeri **Gray**

A perennial herb with stems to 0.8 meters long, *Amsonia palmeri* grows on dry slopes, flats and floodplains in open shrublands. It occurs in the deserts of Arizona, New Mexico, western Texas and adjacent Mexican states.

Buehrer and Benson (15) reported the rubber content of this species (under the name *Amsonia hirtella* Standl.) as 2.53 percent of the whole plant. Although the plants are relatively small, they can be cut and harvested two times a year (41). In addition, their irrigation requirement is low compared to other crops currently being grown in the arid southwestern United States (41). *Amsonia* shows promise as a feedstock for fermentation technology and as an animal feed (41).

Apocynum androsaemifolium **L.,** *A. cannabinum* **L.**

These are perennial herbs less than one meter tall. Both are widespread across the United States. In the Southwest *Apocynum* species generally grow in forests or woods, usually at elevations above 1,525 meters. Elsewhere they are characteristic of prairies, woodland margins, lakeshores, pastures and roadsides.

Rubber content of the whole plant has been variously reported as 0.35 to 0.88 percent (60) and 0.2 to 2.2 percent (38). One sample produced 4.5 to 5.1 percent rubber (38). Fox (33) found two to three percent rubber in the latex. Both species spread by rhizomes and could be vegetatively propagated with ease.

According to Hall and Long (38), the rubber is of high quality. They consider *Apocynum* to be among the most promising genera for further investigation. The sparsely leaved *A. androsaemifolium*, however, produces so little biomass that it can be dismissed out of hand. *Apocynum cannabinum*, a taller and leafier plant, is a more likely candidate. The fiber left as a byproduct of rubber processing makes a fair-quality paper (38).

Asclepiadaceae

Asclepias **spp.**

According to Hall and Long (38), rubber from *Asclepias* is of low grade and best suited for mixing with higher-quality rubbers. Berkman (8) noted that the rubber in many species is present in such low con-

centrations that growing them exclusively for rubber is not commercially feasible but that several species contain potentially useful fiber and seed oil. During World War II, the hairs on the seeds were used as a substitute for kapok (8).

The flowers are constructed in such a way that artificial pollination, while possible, is an extremely time-consuming and tedious procedure with a low success rate (6, 74). This makes it difficult to improve the crop by breeding.

Asclepias albicans **Wats.**

A perennial with many leafless, wandlike stems from the root crown, *Asclepias albicans* is native to the low desert of southeastern California, southwestern Arizona and adjacent Mexico. Usually 1.5 to two meters tall, the plants occasionally reach heights of three meters and are most abundant on steep, rocky slopes. When cultivated in Tucson, Arizona, where winter minima of -5.5 degrees C are not infrequent, *A. albicans* suffered minor frost damage (Steven P. McLaughlin, personal communication). The percentage of rubber, 2.1 to 5.4, is least at the woody base and increases going up the stem (38). Whole-plant rubber contents of 2.14 to 2.93 percent (15) and 0.88 to 4.42 percent (7) have also been reported. The stem wax, a potential coproduct, has a melting point of 84 degrees C (43).

Asclepias californica **Greene**

Native to California and northern Baja California, *A. californica*, a perennial herb to 0.5 meters tall, occurs on dry slopes in chaparral, woodland and open forest. The leaves are large, up to fifteen centimeters long. Leaf rubber content of 4.1 percent has been measured, and the rubber content of the dried latex, ten percent, exceeds that of *Hevea* (38).

Asclepias eriocarpa **Benth.**

A leafy, perennial herb 0.4 to 0.9 meters high, *A. eriocarpa* grows well in hot, dry places, usually below 2,300 meters. It occurs in California and Baja California. Rubber content of the leaves has been reported as 2.4 percent (38).

Asclepias erosa **Torr.**

This perennial herb of desert and grassland can be found along roadsides and in sandy washes in California, Arizona, Nevada and Utah. Its stout stems reach 1.5, occasionally two, meters in height. Plants send up eight to twenty stems from the rootstocks in the spring and mature seeds in the autumn before frost kills them to the ground (7).

Botanists with the USDA Bureau of Plant Industry began investigating this species as a potential rubber plant in 1931 (7). They discovered that wild plants contained 2.45 to 13.06 percent rubber; the progeny of selected plants yielded 4.55 to 11.53 percent rubber. Buehrer and Benson (15) found 2.16 percent rubber in wild accessions and 5.75 percent in irrigated plants. According to Beckett et al. (7), the leaves contain ninety percent of the rubber and represent about fifty percent of the plant dry weight. Seed germinates readily and can be sown directly into field plots (7). The maximum rubber content is attained in the first or second year of growth.

Asclepias latifolia **(Torr.) Raf.**

Although this species seldom exceeds 0.6 meters in height, the leaves are large — up to fifteen centimeters long and nearly as broad. Tolerant of a wide variety of soils, *A. latifolia* grows along roadsides, in old fields and on prairies from Colorado to Oklahoma and northern Mexico. Hall and Long (38) reported its rubber content at two to 3.8 percent. They estimated its potential rubber yield to be 315 kilograms per hectare and regretfully concluded that

this was too low to justify growing it even on cheap land. If its biomass could be increased by selection, they added, *A. latifolia* might be a worthwhile candidate since it could probably be easily cultivated.

Asclepias subulata **Decne.**

Like *Asclepias albicans*, *A. subulata* bears many wandlike, leafless stems from a central crown. The plants are generally one to 1.5 meters high and grow in washes or depressions in the low desert regions of Nevada, California, Arizona and adjacent Mexican states.

Hall and Long (38) reported an average rubber content for the stems of 3.1 percent, which would produce 336 to 560 kilograms of rubber per hectare per crop. Beckett and Stitt (6) found rubber content of wild plants to range from 0.5 to 6.0 percent. Rubber content is least during periods of active growth – May to July – and highest during the dormant period – fall and winter (6, 38). As in *Asclepias albicans*, the greatest concentration of rubber occurs in the non-woody portions of the stem. Plants attain their maximum rubber content at four years of age.

The USDA Bureau of Plant Industry began agronomic work on this species in 1921. In propagating the plants, cuttings, root-crown division and budding were all unsuccessful, but seed germinated readily and seedlings could be easily transplanted. Two-year-old plants in field plots averaged one meter in height and had 121 stems; the following year, the average height increased to 1.2 meters and stem number to 149. Plants produced new stems from the root crown after the tops were cut. Regrowth was most rapid after January or April cuttings. Plants cut in July or October regrew slowly or, in some cases, died. After cutting, plants took three years to reach their maximum size and four years to attain maximum rubber content. Beckett and Stitt (6) concluded that the greatest yield of rubber could be expected from three-year-old plants harvested during a dormant period and cut again at three-year intervals. They obtained a maximum rubber yield of 238 kilograms per hectare with unthinned plants in rows 30.5 centimeters apart.

Beckett and Stitt (6) noted that "the development of high-yielding strains [of *A. subulata*] through selection is likely to prove difficult, as the flowers are self-sterile, artificial pollination is a very slow and tedious process, and vegetative propagation. . .has not proved feasible."

A. subulata shows good potential as a fiber plant, especially for papermaking (38). The stem wax, another potential coproduct, has a melting point of 79.0 degrees C (43) and contains 2.5 percent epicuticular alkane on a dry weight basis (64).

Asclepias sullivanti **Engelm.**

Seldom more than 1.1 meters tall, this is a large-leaved herb that puts up a few stems from a deep-seated rhizome. It can be found along roadsides and on prairies throughout the midwestern United States. Hall and Long (38) reported that this species had the highest rubber content – to 8.2 percent – of any milkweed they tested.

Asclepias syriaca **L.**

The common milkweed of roadsides, floodplains and pastures across much of the eastern and midwestern United States, *Asclepias syriaca* is a leafy, rhizomatous, perennial herb to two meters high.

As is true of other *Asclepias* species, rubber content is highly variable from plant to plant (19, 38). Hall and Long (38) found a maximum of 4.2 percent. Campbell and Carr (19) found a range of 0.3 to 4.6 percent rubber, a far cry from the ten percent that Buchanan and Otey (13) suggested as the economically feasible minimum. The molecular weight of rubber from this species – 120,000 (78) – suggests that it is

not a promising candidate as a rubber crop.

Growth from root cuttings is unsatisfactory (74), but nondormant seeds germinate readily at fourteen to thirty-five degrees C (18). Dormant seeds can be induced to germinate after treatment with gibberellic acid or kinetin (18). The plants require a good supply of water (74) and are susceptible to aphid infestations (18, 74).

Despite claims that genetic variation in *A. syriaca* is great enough to justify a breeding program (18), there is at present no evidence that the observed variation in plant height, rubber content, number of tillers and so forth is actually under genetic control. Breeding of this species is complicated by the difficulty of obtaining fertile crosses (74). Campbell and Carr (19) concluded that, even so, rubber levels of less than ten percent "could be sufficient depending on the value of the polyphenols and oil as industrial raw materials and the feed value of the extract-free meal." *A. syriaca* shows some potential as a fiber plant, especially in papermaking (85).

Cryptostegia grandiflora **R. Br.**

Native to countries bordering on the Indian Ocean, this species has been widely grown as an ornamental in tropical and subtropical regions (50). During World War II, it was cultivated for its rubber in frost-free regions of Arizona, California and Florida. Temperatures of -6.5 degrees C kill the stems to the ground, but they regrow rapidly (63). According to Polhamus et al. (63), the plants are not excessive water users. In habit *C. grandiflora* is a rounded shrub two meters or more tall. It produces whiplike, vining leaders three to six meters long.

Traditionally, it is the whips that have been tapped for rubber; the tips are cut off and the coagulated latex collected by hand (25, 50, 75). Rubber content of the whips is 0.3 to 0.5 percent on a dry-weight basis (9). Stewart et al. (75) estimated that two-year-old plants could provide 135 kilograms of rubber per hectare per year. Estimates as high as 840 kilograms have been made (45). Although the rubber gathered from the whips approaches *Hevea* rubber in quality, daily clipping of stems is a labor-intensive process unsuited to American agricultural practices (25) and hardly economical elsewhere except during emergencies (31). Bhatnagar et al. (9) developed a laboratory method for extracting rubber from partially dried whips.

The rubber percentage of the dried leaves exceeds that of the whips, but, according to Clark (25), it is soft and tacky and of inferior quality. Polhamus et al. (63) found the average leaf rubber content to be 3.13 percent; values as high as 7.19 percent have been obtained (15). Bonner and Galston (10) reported that yields of 225 to 450 kilograms of rubber per hectare per year could be obtained from leaf trimmings. Solvent extraction, the only practical method for obtaining rubber from the leaves (50), results in decreased yields (31).

Cryptostegia adapts well to cultivation and can be planted at densities of 11,200 plants per hectare (45) or even higher; Faulks and McGavack (30) suggested a spacing that would result in 96,800 plants per hectare. Full growth of two meters is attained in a year under the best circumstances (45), and plants cut to the ground annually send up fresh shoots from the rootstocks (50).

Fiber is a potential coproduct (11).

Cryptostegia madagascariensis **Bojer**

A Madagascar native, *C. madagascariensis* is a compact shrub that shows only a slight vining tendency. On the average, its leaves contain a somewhat lower percentage of rubber than *C. grandiflora*: 2.94 percent, with 3.14 percent as the maximum reported (63). Although both species have been used for rubber in India and Madagascar, *C. madagascariensis* has ap-

parently not been commercially exploited to any extent. Its fiber has been used in Madagascar for string, fishing line and cords and might have some commercial value as a coproduct.

Cryptostegia grandiflora **X** *Cryptostegia madagascariensis*

The hybrid between the two *Cryptostegias* shows more promise as a rubber plant than either parent. It is considerably larger and more vigorous than *C. grandiflora* or *C. madagascariensis*, combining the compact growth of the latter with the vining tendency of the former (63). The dried leaves contain an average rubber content of 5.97 percent and a maximum of 8.60 percent (63). Leaf rubber content is at its lowest in the spring, when (in southern Florida) mature leaves are lost and new growth appears. As the season advances, rubber content increases until it reaches a maximum in November and December (63). The hybrid does not come true to type from seed. Air-layering gives better results for propagation than hardwood cuttings, which usually lack vigor or fail to root (63).

Compositae

Cacalia atriplicifolia **L.**

Occurring from the midwestern United States to the Eastern Seaboard, this perennial herb inhabits open woods. Stems reach two meters or more in height.

According to Buchanan et al. (12), Thomas Edison reported a rubber content as high as 4.05 percent; their own samples produced 3.10 percent rubber. Mitchell et al. (53) reported a low of 1.75 percent. *Cacalia* rubber has a molecular weight of 265,000, a value within the range used in commercial rubber production (78). Buchanan et al. (12) claimed that *C. atriplicifolia* compares favorably in terms of rubber with *Parthenium argentatum*, *Asclepias subulata*, *Chrysothamnus nauseosus*, *Taraxacum kok-saghyz* and *Solidago leavenworthii*, and has the potential to be as productive as *Hevea*. Fiber is a potential coproduct (12).

Chrysothamnus nauseosus **(Pall.) Britton**

The various subspecies of *C. nauseosus* can be found throughout the western United States from sea level to 2,745 meters. All are shrubs, some reaching heights of 2.4 meters. They thrive along roadsides, in washes and floodplains, and on rocky slopes and silty flats. Certain subspecies tolerate alkali soils (36). In the wild most or all of the subspecies are self-fertile. This does not rule out the possibility of obtaining artificial hybrids (83) should this prove desirable, and it could be an advantage in selecting strains with high rubber content or other specific traits. Nomenclature for the subspecies mentioned below can be found in Anderson (3).

Hall and Goodspeed (36) suggested the name *chrysil* for the rubber derived from this species. Instead of being contained in latex, the rubber particles occur as solids within the inner bark and outermost wood (36, 38). Hall and Goodspeed (36) reported that the rubber was of good quality and better than that obtained from *Parthenium argentatum*. Clark (25), however, said that "judging from physical properties, the rubber was very low grade." A molecular weight of 45,000 has been reported (83), which seems surprisingly low for "good-quality rubber." The highest rubber percentage found in any individual subspecies of *C. nauseosus* was that for ssp. *turbinatus*—6.67 percent (39). A sample of *C. nauseosus* ssp. *consimilis* approached this value (36). Recently reported values for other subspecies are: *hololeucus*, 2.5 percent (40); *consimilis*, four percent (39); *viridulus*, 2.5 percent (57). Other subspecies tested contained about one percent rubber (57). Hall and

Goodspeed (36) reported these values for additional subspecies: *gnaphalodes*, 0.26 to 3.60 percent; *speciosus*, 0.16 to 2.77 percent; and *graveolens*, 0.07 to 3.19 percent. Although several investigators have suggested that the variation in rubber content among subspecies indicates genetic control (39, 57), the relative contributions of genotype, phenology, morphology and environment have yet to be determined.

In the plants examined, rubber content is highest in the oldest stems near the soil line (39). The percentage of rubber increases rapidly between the third and fifth year, reaching a maximum when the stems are five or six years old (36). Seasonally, rubber content is greatest in the fall (36) or when temperatures are highest and soil moisture is lowest (40).

The plants readily lend themselves to cultivation. Although stem cuttings root poorly, plants can be propagated vegetatively by division and tissue culture (83). Seed germinates best under a regime of cool nights and warm days (83). Growth is relatively rapid for a shrub; according to Hall and Goodspeed (36), stems from three-year-old plants under cultivation weighed as much as 6.8 kilograms. Wild plants in Utah averaged twenty-nine kilograms per plant dry weight. The shrubs regrow rapidly from cut stumps, making it feasible to crop them continuously (36, 57). Ostler et al. (57) calculated that plants containing only two percent rubber would, if planted at a density of 11,964 plants per hectare, yield 598.2 kilograms per hectare in five years. Assuming plants with a rubber content equal to the known maximum of 6.67 percent, the yield would increase to 1,794 kilograms per hectare. At 1983 prices, the value of the rubber would be $1,812 per hectare (57).

Because its rubber content is relatively high and the plants themselves are generally large, *C. nauseosus* has been strongly recommended several times for further development as a rubber crop (36, 57, 82). Hall and Goodspeed (36) specifically point out that it is more cold-tolerant than *Parthenium argentatum*, has a lower water requirement and puts on more biomass. Nevertheless, its low molecular weight is a major constraint to development as a rubber crop.

Other uses, current and potential, include insecticides, fungicides, browse for game animals and livestock, and landscaping (83).

Chrysothamnus paniculatus **(Gray) H. M. Hall**

This rounded shrub to two meters tall grows along roadsides, in washes and on gentle slopes in the deserts of California, Arizona, Nevada and Utah. Samples examined by Hall and Goodspeed (37) contained 1.20 to 3.24 percent rubber. Studies conducted at the Bioresources Research Facility, University of Arizona, suggest that *C. paniculatus* would make a better resin than rubber plant (Steven P. McLaughlin, personal communication).

Chrysothamnus teretifolius **(Dur. & Hilgard) H. M. Hall**

In exceptional circumstances, *Chrysothamnus teretifolius* can reach two meters in height and width, but the plants are usually much smaller. It grows in desert and dry woodland of California, Arizona, Nevada and Utah, often on rocky slopes or canyon walls. Hall and Goodspeed (37) reported that average plants weigh 0.5 to 1.4 kilograms with a rubber content ranging from 1.67 to 4.51 percent. Resin is a potential coproduct (Steven P. McLaughlin, personal communication).

Ericameria laricifolia **(Gray) Shinners**

A rounded shrub 0.3 to one meter tall, *Ericameria laricifolia* occurs on rocky slopes and outcrops at the upper margin of

the desert and in woodland. It can be found from California to western Texas and in adjacent Mexican states. In the literature it is sometimes called *Haplopappus laricifolius* Gray.

Rubber content ranges from 2.01 to 5.16 percent (37).

Ericameria nanum **Nutt.**

Rarely more than 0.3 meter tall, this gnarled and much-branched shrub grows on rocky ledges and outcrops, usually above 1,830 meters, in California, Nevada, Utah and Montana. It also goes under the name of *Haplopappus nanus* (Nutt.) D. C. Eaton.

Hall and Goodspeed (37) stated that its rubber content is six to ten percent of the whole plant, among the highest for any species native to the United States. They note also that the copious resins on the foliage (typical of the genus) might make the rubber inferior to chrysil.

Guardiola platyphylla **Gray**

Often growing in shaded canyon bottoms and open oak woodlands, this perennial herb is native to Arizona and northern Mexico and grows to one meter in height. Buehrer and Benson (15) found rubber content of the whole plant to be 2.33 percent. Carr et al. (23), however, found only 1.5 percent rubber in this species. The molecular weight of the rubber is quite low—49,000 (23).

Helianthus **spp.**

Sixty-nine species and subspecies of *Helianthus* are native to the United States. Stipanovic et al. (76, 77) analyzed fifty-three of these and found rubber concentrations greater than 0.93 percent in the leaves of fourteen. Relatively large quantities of other hydrocarbons contaminated the rubber fraction of many, but Stipanovic et al. (77) noted that the rubber fraction of several species was relatively pure and suggested that these might be worth development as rubber crops. They presented no genetic support for their statement that "there is a high potential for increasing the rubber content of cultivated sunflower" (77). Potential coproducts include specialty carbohydrates such as pectin and inulin, and livestock feed (1).

Helianthus agrestis **Pollard**

An annual to two meters tall, *H. agrestis* grows in damp, mucky soils in Florida and Georgia and requires high humidity for good growth. The leaves contain 1.62 percent rubber (76). This species does not hybridize readily with others in the genus (67), which could place severe constraints on cross-breeding for desirable traits. Since the plants are highly self-fertile, however (67), selection of promising strains within the species could proceed rapidly.

Helianthus annuus **L.**

This annual sunflower reaches 2.5 meters in height and occurs widely throughout North America, commonly in pastures, old fields, roadsides and other disturbed places. The plants tolerate a variety of soil types and do not demand a great deal of water. *H. annuus* is actually a polymorphic complex encompassing many wild and weedy races, in addition to the cultivars that have been bred for fodder, seed and ornament. It hybridizes readily with many other species in the genus (67). Rubber content in wild strains has been variously reported as 0.26 percent, 0.55 percent and 1.45 percent (77). Because it has been successfully bred for diverse purposes and because it crosses so readily with other *Helianthus* species, *H. annuus* might be worth pursuing as a rubber crop despite its relatively low rubber content.

Helianthus californicus **DC.**

A robust perennial herb to five meters tall, this species is native to California and

thrives in moist soil along streams and in marshy meadows. Rubber content of the leaves is 1.79 percent (77). This species can be artificially crossed with *Helianthus resinosus* (67), which might bode well for developing vigorous plants with relatively high rubber content.

Helianthus hirsutus **Raf.**

A common perennial herb one to two meters tall, *H. hirsutus* can be found in dry, open habitats from central Texas to Minnesota, Pennsylvania and Florida. Rubber content of leaves is low, only 0.3 percent (1), but Swanson et al. (78) reported that the rubber has a molecular weight of 279,000. Artificial hybrids have been obtained with *H. annuus* (67).

Helianthus occidentalis **Riddell ssp.** *plantagineus* **(Torr. & Gray) Heiser**

Limited to southeastern Texas and northern Arkansas, this rhizomatous perennial grows to 1.5 meters tall. Its leaf rubber content is 1.62 percent (76). Natural and artificial hybrids with several other *Helianthus* species are known (67).

Helianthus radula **(Pursh) Torr. & Gray**

H. radula, a perennial herb to one meter tall, inhabits sandy soil in pine forests of the southeastern United States. Stipanovic et al. (77) found 1.93 percent rubber in the leaves. Hybridization of this species with others in the genus is uncommon (67).

Helianthus resinosus **Small**

A native of the southeastern United States, where it occurs on bluffs and in dry woods, this rhizomatous perennial reaches three meters in height. According to Stipanovic et al. (77), the leaves contain 1.93 percent rubber. As mentioned above, *H. resinosus* and *H. californicus* can be artificially crossed (67).

Hymenoxys richardsonii **(Hook.) Cockll. var.** *floribunda* **(A. Gray) Parker**

A low, bushy perennial herb to 0.2 meter tall, this species can be abundant on overgrazed ranges and other dry, disturbed sites. It occurs across much of the western United States at elevations between 1,525 and 2,745 meters. This taxon sometimes appears in the rubber literature as *Hymenoxys floribunda* Cockll.

The whole plant contains only about 0.9 percent rubber (4). Greater concentrations are found in the basal stems and roots, where the rubber percentage reaches 3.6 (38). Roots alone contain five to twelve percent rubber mixed with a "considerable proportion" of impurities (38). Feustel and Clark (31) consider *H. richardsonii* var. *floribunda* an unpromising candidate because of the proportion of resin and the low molecular weight and inferior quality of the rubber.

Parthenium argentatum **Gray**

A small, rounded shrub to 0.5 meters high, *Parthenium argentatum*, commonly called guayule, is native to the arid regions of northern Mexico and adjacent Texas, where it reaches its greatest abundance on limestone at elevations of 1,000 to 1,950 meters. Rubber content of native stands varies considerably: in one population, individuals contained 3.6 to 22.8 percent rubber (52). Three-year-old cultivated plants average seven percent rubber (80). Plants can be harvested at three to five years of age. The molecular weight of *P. argentatum* rubber is 1,280,000 (22), a value that compares favorably with *Hevea* rubber and is far higher than the values reported for other rubber plants native to North America. The rubber occurs in individual cells and can be extracted only by extracting the entire plant or its stems.

P. argentatum has been the focus of research and development since the late nineteenth century (20), giving rise to an extensive bibliography (2, 17, 46). The first

guayule-processing factory was constructed in Coahuila, Mexico, in 1902; by 1910, some fourteen factories were in operation in Mexico (20). With the advent of World War II and associated rubber shortages, the U.S. Congress in 1942 authorized the Emergency Rubber Project, which focused attention on guayule as a substitute for *Hevea* rubber. By the end of the war, the 32,000 acres planted to guayule had produced 408,240 kilograms of rubber (32). Native stands were extensively harvested, as well (32). The project was terminated after the war, but interest in guayule continued in both the United States and Mexico (20, 32), culminating in passage of the Native Latex Commercialization and Economic Development Act in 1978. This law authorized $30 million for research and development into the production and commercialization of guayule rubber (32). Current research emphasizes development of high-yielding cultivars by plant breeding (80).

P. argentatum can be grown where annual rainfall ranges from 380 to 635 mm and temperatures seldom fall below -9 degrees C (47). It has been cultivated both under irrigated and dryland conditions. Given the rapidly increasing cost of irrigation energy in the Southwest, guayule should be able to compete successfully with higher-water-use crops such as cotton, sorghum and sugarbeets (32). Agronomic problems have included low germination rates, low seedling survival when seeds are sown directly into the field, competition from weeds, and susceptibility to *Verticillium* wilt, charcoal rot and Texas root rot (32, 61, 80). None of these problems has proved insurmountable; indeed, cultivation practices for *P. argentatum* are well known, and there are no agronomic barriers to commercial production of guayule rubber (32).

The major barrier at present is the need for higher-yielding cultivars. Economic studies indicate that annual rubber yields of 1,000 to 1,800 kilograms per hectare are necessary to meet the current costs of production in Texas and Arizona (80). Actual yields are now about half that amount, but development of cultivars that can produce 1,200 kilograms rubber per hectare per year is highly probable (80). Plant breeders are making increasing use of diploid lines, some of which contain greater than fifteen percent rubber (52), and they are also crossing diploid *P. argentatum* with other species in the genus to obtain greater cold tolerance, increased biomass, greater disease resistance and higher regrowth after clipping (80).

Resin is a potential coproduct (20); resin yields may exceed that of rubber, especially in irrigated plants (80).

Scorzonera tau-saghyz Lipschitz & Bosse

S. tau-saghyz, a perennial herb native to Kazakhstan in the Soviet Union, resembles a dandelion in its taproot and basal rosette of leaves. In its native climate it tolerates severe winters, dry summers, a short growing season and low annual precipitation (61). Rubber comprises up to thirty percent or more of the dry weight of the root (the highest of any known rubber-bearing plant) but may require as many as five years to reach this concentration (61). Under cultivation in Great Britain, the seeds germinated poorly outdoors and transplants proved difficult to establish (50). Bonner and Galston (10) noted that commercial exploitation of this species is unlikely because the plants are susceptible to fungal and insect infestations.

Solidago spp.

Species in this genus have received a good deal of attention as potential sources of domestic rubber. In *Solidago* the rubber occurs as globules in the cells, not as particulates in latex. Of the twenty-four

species Polhamus (59) tested, eleven contained three percent or more of rubber in the leaves. (Stems and roots contained little or none.) Polhamus pointed out that such species as *S. minor* Fern. and *S. tenuifolia* Pursh, although relatively rich in rubber, have such small leaves that they would be poor candidates for a rubber crop. Rubber accumulates in the leaves as the growing season advances and reaches a maximum when the leaves are fully mature. In most species, the leaves are shed soon after they reach maturity. Because the stems typically grow from an extensive system of branching rhizomes, the plants can probably be cut and reharvested at least once during the growing season.

The molecular weight of *Solidago* rubber is low. Swanson et al. (78) reported an upper limit of 200,000, which means that the rubber is of marginal usefulness. Slight prevulcanization improves processability, overcoming to some extent the low molecular weight (78). Feustel and Clark (31) considered *Solidago* "a relatively unattractive source of rubber" because of the need for additional processing. Clark (25) pointed out that because the rubber is sticky, it is difficult to process with conventional rubber machinery. Because of the need for special processing, there is little likelihood that *Solidago* rubber could be competitive with *Hevea* or *Parthenium* except during emergencies (61).

Some *Solidago* species show potential as fiber plants (11).

Solidago altissima **L.**

Occurring from the Atlantic-coast states to Arizona and Wyoming, this leafy perennial herb attains one to two meters in height. It prefers open places such as old fields, woodland clearings and marsh edges. Polhamus (59) found rubber content to range from 1.38 to 6.34 percent with a mean of 3.45 percent. The molecular weight of the rubber is 239,000 (78). Certain authors treat this taxon as a variety of *Solidago canadensis* L. Fiber is a potential coproduct (11).

Solidago fistulosa **Mill.**

Native from New Jersey south to Florida and Louisiana, *S. fistulosa* attains a height of 1.5 meters and grows in damp places such as pond borders and marshes. It can also be found in dry pine forests. According to Polhamus (59), the rubber percentage ranges from 2.08 to 4.48 with a mean of 2.99.

Solidago leavenworthii **Torr. & Gray**

Occurring naturally in Florida, this species—known as Edison's goldenrod—has been cultivated for rubber in Maryland, where its growth was poor, and in South Carolina, Georgia, Mississippi, Louisiana, New Mexico and California, where growth was satisfactory (61). In the wild, its range of habitats includes roadsides, floodplains, and pond margins. The plants are intolerant of cold winters and probably cannot be grown outside the southern tier of states. Through selection and breeding, the rubber content of the leaves was raised to about four percent (25). This species has been treated in the literature as *Solidago edisoniensis*. Fiber is a potential coproduct (11).

Solidago rugosa **Mill.**

Native from the midwestern United States to the Atlantic-coast states, this very leafy plant grows to 1.5 meters tall. It generally occurs in wet, open habitats. Polhamus (59) reported the rubber content to range from 2.63 to 3.54 percent with a mean of 2.95 percent.

Solidago sempervirens **L.**

Occurring in the Atlantic-coast states and on the Gulf coast of Louisiana, *S. sempervirens* can be found at the borders of tidal marshes and in moist pine forests. The stems reach two meters in height. The

mean rubber percentage is 3.02; it ranges from 2.22 to 3.94 (59).

Soliago serotina **Kuntze**

Growing to two meters tall, this species occurs from southern Canada to Georgia and New Mexico, usually in moist, open places. According to Polhamus (59), rubber content ranges from 2.40 to 5.64 percent, with a mean of 3.92 percent. Some authors treat this taxon as *S. gigantea* Ait. var. *serotina* (Kuntze) Cron.

Taraxacum kok-saghyz **Rodin**

Like *Scorzonera tau-saghyz, T. kok-saghyz* is a dandelionlike plant with a basal rosette of leaves and a thickened taproot. It, too, is native to the mountains of Kazakhstan, and although the roots contain less rubber than those of *Scorzonera*, the plants have proved somewhat more amenable to cultivation (50, 84). Although a perennial in the wild, it is treated in cultivation as an annual or biennial, and a rubber harvest can be obtained within a single growing season (84).

Rubber content in unimproved strains is highly variable, from a trace to thirty percent; roots selected for high rubber contain from twelve to twenty-two percent (84). Under cultivation in the northern United States, *T. kok-saghyz* yielded an average of fifty kilograms per hectare. In the Soviet Union, yields as high as sixty-seven kilograms per hectare have been reported (84). It is a high-quality rubber that performs as satisfactorily as *Hevea* rubber in heavy-duty tires and is much superior to *Parthenium* rubber (84).

In the United States, *T. kok-saghyz* grew best in the northern third of the country (84). Performance was poor where summers were long and hot. In the southern states, it performed best as a winter crop where temperatures do not fall below -3.9 degrees C (84). It tolerates a variety of soil types as long as they are well fertilized and not stony, steep or poorly drained. Cultural problems include seed dormancy, high percentage of abnormal germination, slow germination, and weak and slow-growing seedlings (84).

Whaley and Bowen (84) felt highly encouraged by the gains made in breeding for greater rubber percentage, and stated that "if increases in rubber content and root yield of kok-saghyz can be accompanied by marked improvement in the general vigor of the plant, economical production of the crop may become a distinct possibility" (84).

Taraxacum megalorhizon **Hand.-Mzt.**

Native to the Crimean region, this taprooted perennial can be easily cultivated, but the rubber is not as easily extracted from the root nor as copious as in *T. kok-saghyz* (50). After two years the root rubber content ranges from five to eight percent (10). Bonner and Galston (10) did not consider this species to be commercially exploitable.

Euphorbiaceae

Euphorbia **spp.**

According to Polhamus (61), some forty-four species of *Euphorbia* are known to contain rubber. Most of these are latex-bearing trees or shrubs whose rubber is obtained by tapping. The feasibility of growing shrubby *Euphorbias* as agricultural crops has not been determined, but there is a precedent in *Parthenium argentatum*, a shrub that is harvested for its rubber after three to five years of growth. The *Euphorbia* species native to arid and semiarid regions are drought-resistant and might do well in the warmer parts of the southwestern United States where frost is infrequent.

Euphorbia balsamifera **Ait.**

Native to the Sahelian region of Africa,

E. balsamifera is a shrub to 1.5 meters tall. Its succulent, limber stems yield abundant latex that contains up to twenty percent rubber of good quality after deresination (61).

Ephorbia resinifera **Berg.**

This species is a slow-growing, succulent perennial that forms mounds to 1.5 meters tall and ten meters across. It grows in the Atlas Mountains of Morocco, where it prefers rocky slopes and bedrock outcrops. Its native climate features hot, dry summers and mild wet winters; it is reported to tolerate light frost (55). Polhamus (61) stated that its latex contains up to twenty percent good-quality rubber after deresination.

Jatropha cardiophylla **(Torr.) Muell.-Arg.**

A shrub to 1.5 meters tall with several to many wandlike stems from the central crown, *Jatropha cardiophylla* bears leaves for only two or three months in the summer. It is native to the deserts in Arizona and adjacent Mexico, and typically grows on rocky slopes. In the vicinity of Tucson, Arizona, frost damage to the stem tips is common most years, and the plants freeze back nearly to the ground during the coldest winters. Wild plants propagate more often by rhizomes than by seed.

Hall and Long (38) reported that the stems contain three percent rubber.

Pedilanthus bracteatus **(Jacq.) Boiss.**

A shrub one to three meters tall with thick, succulent stems and medium-size to large leaves, *P. bracteatus* occurs on the coastal plain of Mexico from southern Sonora to Oaxaca. The latex reportedly contains twenty-eight percent rubber (65).

Pedilanthus macrocarpus **Benth.**

A clump-forming, succulent perennial to one meter tall, *P. macrocarpus* has many waxy, leafless stems from the base. When cut, they exude copious latex. The species is locally common in the deserts of Baja California and coastal Sonora. The plants are not hardy at Tucson, Arizona, where winter minima of -5.5 degrees C occur predictably.

Sternberg and Rodriguez (73) found that purified rubber constitutes six to ten percent of the fresh weight of the latex. They considered the rubber yield and quality to compare favorably with present commercial sources. Extensive harvesting of native stands for rubber was carried out briefly in the 1940s (86). The stem wax, a potential coproduct, contains 3.4 percent epicuticular alkane on a dry weight basis (64).

Labiatae

Evidently a number of species in the Labiatae produce natural rubber (11, 12), but in most cases the quantities are so low that it is not practical to grow the plants for rubber alone. Buchanan et al. (11, 12), who have identified several species in this family as potential rubber crops, did so based on the assumption that selection and breeding could increase plant biomass and rubber content.

Monarda fistulosa **L.**

A perennial herb to 1.2 meters tall, *Monarda fistulosa* grows from creeping rhizomes. It is distributed across much of the Midwest to the Rocky Mountains and the southeastern United States. At least two varieties have been described; var. *menthifolia* (Grah) Fern. is often found in moist places, such as ditches, lakeshores, streambeds and wet meadows; var. *fistulosa* occurs in somewhat drier habitats, such as prairies, roadsides and open woods.

Buchanan et al. (11) noted that rubber contents of 1.5 to 2.5 percent have been reported in the literature; they found 1.15 percent. According to Swanson et al. (78),

the molecular weight of the rubber—419,000—puts it well within the range used in commercial rubber production. Fiber is a potential coproduct (11).

Pycnanthemum incanum **(L.) Mich.**

Growing in upland woods from Vermont and New York to Ohio and Illinois on the west and North Carolina and Tennessee on the south, *P. incanum* is a perennial herb that reaches one meter in height.

Whole plants contain 1.15 percent rubber (12) with a molecular weight of 495,000 (78). Although the rubber content is not high, the molecular weight of its rubber makes *P. incanum* a more attractive candidate than it would otherwise be. Buchanan et al. (12) also noted that the species produces essential oils that might increase its value as a crop.

Appendix B
Profile of Selected Rubber-Producing Plants

Scientific name:	*Amsonia palmeri*
Family:	Apocynaceae
Geographical region:	southwestern United States
Rubber analysis:	2.53 percent rubber (whole plant)
Coproducts:	fermentation feedstock, animal feed

Scientific name:	*Apocynum androsaemifolium, A. cannabinum*
Family:	Apocynaceae
Geographical region:	United States
Rubber analysis:	0.35 to 5.1 percent rubber (whole plant)
Coproducts:	bast fiber

Scientific name:	*Asclepias albicans*
Family:	Asclepiadaceae
Geographical region:	southwestern United States
Rubber analysis:	0.88 to 5.4 percent rubber (whole plant)
Coproducts:	wax

Scientific name:	*Asclepias californica*
Family:	Asclepiadaceae
Geographical region:	California
Rubber analysis:	4.1 percent rubber (leaves) 10 percent rubber (dried latex)

Scientific name:	*Asclepias eriocarpa*
Family:	Asclepiadaceae
Geographical region:	California
Rubber analysis:	2.4 percent rubber (leaves)

Scientific name:	*Asclepias erosa*
Family:	Asclepiadaceae
Geographical region:	southwestern United States
Rubber analysis:	2.45 to 13.0 percent rubber (whole plant)

Natural Rubber-Producing Plants for the United States

Scientific name:	*Asclepias latifolia*
Family:	Asclepiadaceae
Geographical region:	central United States
Rubber analysis:	3.8 percent rubber (whole plant)
Scientific name:	*Asclepias subulata*
Family:	Asclepiadaceae
Geographical region:	southwestern United States
Rubber analysis:	0.5 to 6.0 percent rubber (whole plant)
Coproducts:	wax, bast fiber
Scientific name:	*Asclepias sullivanti*
Family:	Asclepiadaceae
Geographical region:	midwestern United States
Rubber analysis:	8.2 percent rubber (whole plant)
Scientific name:	*Asclepias syriaca*
Family:	Asclepiadaceae
Geographical region:	eastern and midwestern United States
Rubber analysis:	0.3 to 4.6 percent rubber (whole plant)
Molecular weight:	120,000
Coproducts:	seed oil, animal feed, bast fiber
Scientific name:	*Cacalia atriplicifolia*
Family:	Compositae
Geographical region:	midwestern and eastern United States
Rubber analysis:	1.75 to 4.05 percent rubber (whole plant)
Molecular weight:	265,000
Coproducts:	bast fiber
Scientific name:	*Chrysothamnus nauseosus*
Family:	Compositae
Geographical region:	western United States
Rubber analysis:	0.07 to 6.67 percent rubber (whole plant)
Molecular weight:	45,000
Coproducts:	insecticides, fungicides, browse plant, ornamental plant
Scientific name:	*Chrysothamnus paniculatus*
Family:	Compositae
Geographical region:	southwestern United States
Rubber analysis:	1.20 to 3.24 percent rubber (whole plant)
Coproducts:	resin

(Continued next page)

Scientific name:	*Chrysothamnus teretifolius*
Family:	Compositae
Geographical region:	southwestern United States
Rubber analysis:	1.67 to 4.51 percent rubber (whole plant)
Coproducts:	resin

Scientific name:	*Cryptostegia grandiflora*
Family:	Asclepiadaceae
Geographical region:	tropical Asia
Rubber analysis:	0.3 to 0.5 percent rubber (stem tips) 3.13 to 7.19 percent rubber (leaves)

Scientific name:	*Cryptostegia madagascariensis*
Family:	Asclepiadaceae
Geographical region:	Madagascar
Rubber analysis:	2.94 to 3.14 percent rubber (leaves)
Coproducts:	bast fiber

Scientific name:	*Cryptostegia grandiflora* X *Cryptostegia madagascariensis*
Family:	Asclepiadaceae
Geographical region:	hybrid found in cultivation
Rubber analysis:	5.97 to 8.60 percent rubber (leaves)

Scientific name:	*Ericameria laricifolia*
Family:	Compositae
Geographical region:	southwestern United States
Rubber analysis:	2.01 to 5.16 percent rubber (whole plant)

Scientific name:	*Ericameria namum*
Family:	Compositae
Geographical region:	western United States
Rubber analysis:	6 to 10 percent rubber (whole plant)

Scientific name:	*Euphorbia balsamifera*
Family:	Euphorbiaceae
Geographical region:	Sahelian Africa
Rubber analysis:	up to 20 percent rubber (latex)

Scientific name:	*Euphorbia resinifera*
Family:	Euphorbiaceae
Geographical region:	northern Africa
Rubber analysis:	up to 20 percent rubber (latex)

(Continued next page)

Natural Rubber-Producing Plants for the United States

Scientific name:	*Guardiola platyphylla*
Family:	Compositae
Geographical region:	southwestern United States
Rubber analysis:	1.5 to 2.33 percent rubber (whole plant)
Molecular weight:	49,000

Scientific name:	*Helianthus agrestis*
Family:	Compositae
Geographical region:	southeastern United States
Rubber analysis:	1.62 percent rubber (leaves)

Scientific name:	*Helianthus annuus*
Family:	Compositae
Geographical region:	North America
Rubber analysis:	0.26 to 1.45 percent rubber (leaves)
Coproducts:	animal fodder, seed oil, ornamental plant

Scientific name:	*Helianthus californicus*
Family:	Compositae
Geographical region:	California
Rubber analysis:	1.79 percent rubber (leaves)

Scientific name:	*Helianthus hirsutus*
Family:	Compositae
Geographical region:	midwestern and eastern United States
Rubber analysis:	0.3 percent rubber (leaves)
Molecular weight:	279,000

Scientific name:	*Helianthus occidentalis* ssp. *plantagineus*
Family:	Compositae
Geographical region:	southeastern United States
Rubber analysis:	1.62 percent rubber (leaves)

Scientific name:	*Helianthus radula*
Family:	Compositae
Geographical region:	southeastern United States
Rubber analysis:	1.93 percent rubber (leaves)

Scientific name:	*Helianthus resinosus*
Family:	Compositae
Geographical region:	southeastern United States
Rubber analysis:	1.93 percent rubber (leaves)

(Continued next page)

Scientific name:	*Hymenoxys richardsonii* var. *floribunda*
Family:	Compositae
Geographical region:	western United States
Rubber analysis:	0.9 percent rubber (whole plant) 5 to 12 percent rubber (roots)
Scientific name:	*Jatropha cardiophylla*
Family:	Euphorbiaceae
Geographical region:	southwestern United States
Rubber analysis:	3 percent rubber (stems)
Scientific name:	*Monarda fistulosa*
Family:	Labiatae
Geographical region:	United States
Rubber analysis:	1.5 to 2.5 percent rubber (whole plant)
Molecular weight:	419,000
Coproducts:	bast fiber
Scientific name:	*Parthenium argentatum*
Family:	Compositae
Geographical region:	northern Mexico and adjacent Texas
Rubber analysis:	3.6 to 22.8 percent rubber (whole plant)
Molecular weight:	1,280,000
Coproducts:	resin
Scientific name:	*Pedilanthus bracteatus*
Family:	Euphorbiaceae
Geographical region:	central Mexico
Rubber analysis:	28 percent rubber (latex)
Scientific name:	*Pedilanthus macrocarpus*
Family:	Euphorbiaceae
Geographical region:	northern Mexico
Rubber analysis:	6 to 10 percent rubber (latex)
Coproducts:	wax
Scientific name:	*Pycnanthemum incanum*
Family:	Labiatae
Geographical region:	eastern United States
Rubber analysis:	1.15 percent rubber (whole plant)
Molecular weight:	495,000
Coproducts:	essential oils
Scientific name:	*Scorzonera tau-saghyz*
Family:	Compositae
Geographical region:	southwestern Soviet Union
Rubber analysis:	30 percent rubber (roots)

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Scientific name: *Solidago altissima*
Family: Compositae
Geographical region: United States
Rubber analysis: 1.38 to 3.45 percent rubber (whole plant)
Molecular weight: 239,000
Coproducts: bast fiber

Scientific name: *Solidago fistulosa*
Family: Compositae
Geographical region: eastern United States
Rubber analysis: 2.08 to 4.48 percent rubber (whole plant)

Scientific name: *Solidago leavenworthii*
Family: Compositae
Geographical region: Florida
Rubber analysis: 4 percent rubber (leaves)
Coproducts: bast fiber

Scientific name: *Solidago rugosa*
Family: Compositae
Geographical region: eastern and midwestern United States
Rubber analysis: 2.63 to 3.54 percent rubber (whole plant)

Scientific name: *Solidago sempervirens*
Family: Compositae
Geographical region: eastern United States
Rubber analysis: 2.22 to 3.94 percent rubber (whole plant)

Scientific name: *Solidago serotina*
Family: Compositae
Geographical region: United States
Rubber analysis: 2.40 to 5.64 percent rubber (whole plant)

Scientific name: *Taraxacum kok-saghyz*
Family: Compositae
Geographical region: southwestern Soviet Union
Rubber analysis: trace to 30 percent rubber (roots)

Scientific name: *Taraxacum megalorhizon*
Family: Compositae
Geographical region: southwestern Soviet Union
Rubber analysis: 5 to 8 percent rubber (roots)

Appendix C
Catalogue of Selected Tropical Rubber Plants

Apocynaceae

Funtumia elastica **Stapf**

A forest tree of tropical Africa, *Funtumia elastica* was at one time an important commercial source of rubber in Africa (54), where it was extensively planted in the first decade of this century (61). It thrives where the climate is too dry for *Hevea*, and it is less susceptible to insect attacks (61). These advantages as a plantation crop are offset by several drawbacks: tapping eventually results in the death of the tree; the first tap yields only 113.4 grams of rubber, and successive taps yield less and less; the plants are susceptible to root diseases; and as many as twenty years are required to bring a planting to its maximum yield (45, 61).

Landolphia **sp.**

More than twenty species in the genus *Landolphia*, mostly woody lianas and climbing shrubs native to tropical Africa, have been exploited for rubber (61). Few are well-adapted to cultivation in plantations. In general, *Landolphia* species produce excellent quality rubber that is eighty-nine to ninety percent hydrocarbon (45). For most species, an individual vine yields about twenty-eight to 227 grams of rubber with every tapping (45). Tapping can be repeated every three to four months. The most important species are the following:

Landolphia heudelotii **A. DC.**

An annual yield of 2.7 to 3.2 kilograms of rubber was obtained from mature plants in the wild (61).

Landolphia kirkii **Dyer**

A woody liana native to East Africa, *L. kirkii* was at one time an important rubber source in Angola, Zaire, Kenya, Mozambique and Malawi (66).

Landolphia owariensis **Beauv.**

This was once the chief rubber-bearing liana over much of central Africa (61). The latex contains twenty-four percent rubber (56).

Landolphia thollonii **Dewevre**

The portion of *L. thollonii* harvested for rubber is the rhizome bark, the latex of which contains fifteen to sixteen percent rubber (45, 50).

Euphorbiaceae

Euphorbia fulva **Stapf**

Native to the subtropical forests of central Mexico, where it grows on rocky hillsides, *Euphorbia fulva* is a tree up to ten meters tall. The latex contains eighteen to twenty percent rubber and up to forty percent resin (72). According to Stapf (72), the rubber is of good quality, and an excellent varnish can be made from the resin. Each tapping yields an average of one liter

of latex per tree, and trees can be tapped about three times a year (72). A plantation of 100,000 trees would, at this rate, yield 54,000 to 60,000 kilograms of rubber and 120,000 kilograms of resin per year (72).

Euphorbia intisy **Drake**

Once abundant in the arid region of southern Madagascar, this bushy shrub or small tree to seven meters tall was nearly wiped out by ruthless rubber tapping after its discovery in 1891 (79). The rubber is of high quality, by far the best produced by any *Euphorbia* (61). Adaptations to its arid climate include the swollen, water-storing roots and the chlorophyllous, virtually leafless stems (79). Although the feasibility of growing *E. intisy* as a crop plant in the United States has yet to be tested, it is worth noting that Calvin (16) grew the related *Euphorbia tirucalli* L. in plantations in southern California.

Manihot dichotoma **Ule**

This tall, slender tree, a native of Brazil, occurs in semi-arid regions where there are distinct wet and dry seasons. The rubber, which is obtained by tapping, is of "the first order" and constitutes fifteen to thirty percent of the latex (70). Although wild stands were extensively harvested during World War II and many plantings were made during an earlier Brazilian rubber boom, little has been done in the way of selection and improvement of this species (70). Once a commercial rubber plant of some importance (54), *M. dichotoma* eventually failed to compete with *Hevea* because of lower yields (a result of the smaller size of the trees) and the difficulty of tapping the horny outer bark (70).

Manihot glaziovii **Muell.-Arg.**

This species, a forest tree with a diameter at breast height of seventy-five centimeters, is native to Brazil, where it occurs in semi-arid regions characterized by pronounced wet and dry seasons (70). The latex contains fifteen to thirty percent rubber that is equal to *Hevea* rubber in quality, although not in yield (70). The rubber is obtained by tapping, a procedure made rather difficult by the horny outer bark. Yields of up to 4.5 kilograms of rubber per year have been reported for exceptional trees (45). Extrapolated to a planting of 750 trees per hectare, a yield of 3,360 kilograms per hectare per year might be obtained. The usual yield for trees planted at this density, however, is no more than 224 kilograms per hectare per year (45). *M. glaziovii* was once a major competitor of *Hevea* and, as of 1962, was still the most widely planted of the rubber-producing *Manihots* (61). Its low yield relative to *Hevea* and the difficulty in tapping the trees has lessened its importance as a commercial rubber tree (61).

Micandra minor **Benth.**

A rather close relative of *Hevea*, *Micandra minor* is a large tree to thirty-five meters tall. It is abundant on high river banks in the Amazon Valley and the upper Orinoco basin. The trees have been occasionally tapped for their high-quality rubber, but they do not withstand repeated tapping and therefore have not been exploited commercially to any extent (61, 71).

Moraceae

Castilla elastica **Cervantes and** *Castilla ulei* **Warburg**

Native to Central America and the tropical regions of South America, *Castilla elastica* is a large tree twenty meters or more in height with conspicuous, buttressed roots. It occurs in forest clearings or sparsely wooded valley bottoms. *C. ulei*, an even larger tree to forty meters, occurs widely in Brazil. Both have been harvested extensively for rubber, probably from

prehistoric times, and will be discussed together here.

Cook (26) estimated that 8,100 hectares in Central America and southern Mexico were planted to *Castilla*. He noted that the most rapid growth was obtained where the plants were not shaded, and recommended planting them in rows 3.7 to 6.1 meters apart with 2.4 to 3.7 meters between trees in the rows. Propagation from cuttings is easy and affords the best means of selection and improvement (26).

Rubber constitutes over ninety percent of the solid material in *Castilla* latex (61) and is scarcely inferior to that from *Hevea* (38). The younger the tree, the greater the proportion of resin in the latex (26). Copious latex flows from a single tapping, but each tree can be tapped only one to four times a year (61), and a worker can tap only twenty trees a day (*Hevea* workers can tap up to twenty times as many). In addition, the trees, while fast-growing, cannot be tapped for the first eight to ten years of growth. All this combines to make *Castilla* rubber yields lower than those of *Hevea* and to make it less satisfactory as a plantation crop (61). Cook (26) stated that twelve-year-old trees can be expected to yield a maximum of 0.9 kilograms of rubber per year. Polhamus (61) concluded from plantings of *Castilla* in Puerto Rico and Florida that this species could not equal *Parthenium argentatum* in rubber yield.

Ficus elastica Roxb.

About twenty-eight species of *Ficus* have been exploited for their rubber. *Ficus elastica*, a tree native to tropical Asia, is the only one that has seen much commercial use. Although considerable acreage of this species was cultivated in the early days of rubber plantations, it soon gave way to *Hevea* in most areas (61). The trees are not tapped until they reach about twenty-five years, but then they can be tapped four times a year for many decades (66). The rubber has a high resin content (66).

Ficus vogelii Miq.

This species was the chief source of *Ficus* rubber in Africa, where it is native to the tropics (61). Martin (45) noted that a single tree can produce up to 4.5 kilograms of solids per year. Polhamus (61) noted that the rubber is of low quality, but according to Roecklein (66), it is of good quality with a high resin content.

Appendix D
Selected Rubber-Producing Plants Analyzed by Thomas A. Edison

Note: Data for the following table have been extracted from Polhamus (61), who also gives authorities for the names.

Family	Species	Mean Rubber Percent
Apocynaceae	*Rhabdadenia corallicola*	2.77
	Tabernaemontana coronaria	2.04
Asclepiadaceae	*Asclepias speciosa*	2.71
	Asclepias syriaca	2.10-2.35
	Asclepias tomentosa	2.40
	Asclepias tuberosa	2.92
Avicenniaceae	*Avicennia nitida*	2.07
Boraginaceae	*Cordia sebestena*	2.75
Caryophyllaceae	*Paronychia rugelii*	2.04
Compositae	*Aster cordifolius*	2.56
	Aster laevis	2.43-2.65
	Aster paniculatus	2.68
	Aster sagittifolius	2.42-3.63
	Aster umbellatus	1.06-3.44
	Aster undulatus	1.92-2.58
	Cacalia atriplicifolia	2.14
	Cacalia ovata	2.01
	Echites umbellata	2.63
	Erechtites hieracifolia	2.14
	Erigeron strigosus	2.29
	Gnaphalium obtusifolium	2.34
	Helianthus radula	2.54
	Inula helenium	2.43
	Liatris spicata	2.07
	Pterocaulon pycnostachyum	2.23
	Solidago bicolor	2.34

Natural Rubber-Producing Plants for the United States

Family	Species	Mean Rubber Percent
Compositae	*Solidago canadensis*	2.15-2.45
	Solidago elliottii	2.70-3.17
	Solidago erecta	2.64
	Solidago gigantea	2.18-3.54
	Solidago juncea	2.46
	Solidago nemoralis	2.58
	Solidago odora	2.10-3.16
	Solidago patula	2.36-2.92
	Solidago petiolaris	2.56
	Solidago puberula	2.13
	Solidago rugosa	2.46-3.20
	Solidago speciosa	2.21-2.85
	Solidago squarrosa	2.07
	Solidago tenuifolia	2.65
	Solidago tortifolia	2.48
	Solidago ulmifolia	3.00
Hippocrateaceae	*Hippocratea volubilis*	2.31
Labiatae	*Conradina grandiflora*	2.24
	Monarda fistulosa	1.64-2.36
	Pycnanthemum virginianum	2.11
Onagraceae	*Epilobium angustifolium*	2.61
	Oenothera biennis	2.37
Rubiaceae	*Borreria ocimoides*	2.06
	Chiococca racemosa	3.31
Sapotaceae	*Bumelia angustifolia*	2.90
	Bumelia lyciodes	2.34
	Bumelia reclinata	2.12
	Manilkara zapotilla	2.86

Natural Rubber-Producing Plants for the United States

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